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Angeloudis, Athanasios ORCID: <https://orcid.org/0000-0001-5021-3643>,
Falconer, Roger A. ORCID: <https://orcid.org/0000-0001-5960-2864>, Bray,
Samuel and Ahmadian, Reza ORCID: <https://orcid.org/0000-0003-2665-4734>
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Representation and Operation of Tidal Energy Impoundments in a Coastal Hydrodynamic Model

Athanasios Angeloudis, Roger A. Falconer, Samuel Bray, Reza Ahmadian

¹ Hydro-environmental Research Centre, School of Engineering, Cardiff University, the Parade, Cardiff, UK

*angeloudisa@cf.ac.uk

ABSTRACT

A methodology associated with the simulation of tidal range projects through a coastal hydrodynamic model is discussed regarding its capabilities and limitations. Particular focus is directed towards the formulations imposed for the representation of hydraulic structures and the corresponding model boundary conditions. Details of refinements are presented that would be applicable in representing the flow (and momentum flux) expected through tidal range turbines to inform the regional modelling of tidal lagoons and barrages. A conceptual tidal lagoon along the North Wales coast, a barrage across the Severn Estuary and the Swansea Bay Lagoon proposal are used to demonstrate the effect of the refinements for projects of a different scale. The hydrodynamic model results indicate that boundary refinements, particularly in the form of accurate momentum conservation, have a noticeable influence on near-field conditions and can be critical when assessing the environmental impact arising from the schemes. Finally, it is shown that these models can be used to guide and improve tidal impoundment proposals.

Keywords: Numerical Modelling, Renewable Tidal Energy, Severn Barrage, Swansea Bay Lagoon, Tidal Range Power.

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1 INTRODUCTION

Rapid growth has been reported on the wind, solar, wave and tidal renewable energy technologies, towards reducing the dependence on depleting fuels (Dincer, 2000, Kadiri et al., 2012). The UK, in particular, can rely on a significant proportion of its national electricity energy needs on some of the largest tides in the world (Roberts et al., 2016; Yates et al., 2013a; Mackay, 2009; Baker, 1987). By further taking into account international commitments to meet 15% of its energy needs from renewable sources by 2020 (Kirby and Retiere, 2009), there is an interest in extracting the resource offered through tidal range projects.

Tidal range structures operate on the principle of creating an artificial hydraulic head difference by impounding water, and then allowing it to flow through turbines to generate electricity. The potential power (P) is fundamentally proportional to the impounded wetted plan surface area (A) and the square of the water head difference (H^2) facilitated between the upstream and downstream sides of the impoundment:

$$P \propto A \cdot H^2 \quad (1)$$

The most characteristic example of a tidal range energy scheme is the 240 MW La Rance barrage in France, which has been successfully in operation since 1966. However, it is well established that impoundments can lead to regional hydrodynamic regime alterations, which entail implications for existing water quality processes (Kadiri et al., 2012; Wolf et al., 2009). There is additionally a wide spectrum of influential factors which need to be considered, including: structural, geotechnical, electrical, mechanical or socio-economic considerations, which have been highlighted as key aspects for the viability of such tidal renewable energy schemes (e.g. Prandle, 1984; Baker, 1987; Hammons, 1993; Baker et al., 2006; Wolf et al., 2009; Hooper and Austen, 2013; Angeloudis et al., 2016).

There is, therefore, an incentive for the development of numerical modelling tools for the design optimisation of tidal impoundment projects to minimise uncertainties by providing an insight into their potential and impacts. These numerical tools extend from simplified theoretical and zero-dimensional models (Angeloudis et al., 2016; Aggidis and Benzon, 2013; Prandle, 2009; Prandle, 1984) to more sophisticated multidimensional tools (Angeloudis et al., 2016; Angeloudis and Falconer, 2016; Cornett et al., 2013; Yates et al., 2013a,b; Ahmadian et al., 2010; Xia et al., 2010a, 2010b, 2010c; Zhou et al., 2014a, 2014b; Burrows et al., 2009a, 2009b) that often require High Performance Computing (HPC) capabilities (Wolf et al., 2009) to be practically applicable. Most importantly, the reliability of such modelling studies is dependent on the assumptions underpinning the inherent basic fluid mechanics.

This study focuses on a methodology for the representation of the hydraulic structures in a 2-D coastal hydrodynamic model adapted to assess tidal range projects in terms of their operation (Angeloudis et al., 2015; Xia et al., 2010a, 2010b, 2010c). Attention is given to the effect of certain boundary condition assumptions commonly included in many numerical

models, primarily relating to the need to include momentum – as well as mass – conservation in predicting the hydrodynamic conditions prevailing in practise at the design scale for tidal range structures. Three schemes were examined: (a) a hypothetical intermediate size lagoon off the North Wales coast (hereinafter referred to as the Clwyd Impoundment), (b) a smaller scale tidal lagoon concept under consideration for Swansea Bay in the Bristol Channel (Swansea Bay Lagoon) and (c) a larger scale proposal for a barrage (based on the original STPG scheme for the Severn Barrage) within the Severn Estuary (Figure 1). The objectives of this work can be summarised as follows, to:

- (i) Review the formulations and assumptions associated with the modelling of tidal range schemes in the context of a regional hydrodynamic model;
- (ii) Elucidate, based on 2-D hydrodynamic simulation results, the influence of tidal range structure boundary treatment on the numerical model predictions;
- (iii) Demonstrate the significance of certain assumptions, particularly associated with the treatment of momentum conservation, depending on the scale and the design of individual projects; and
- (iv) Illustrate the potential of these impoundments and highlight how these models can be powerful tools to optimise the designs of future and ongoing proposals.

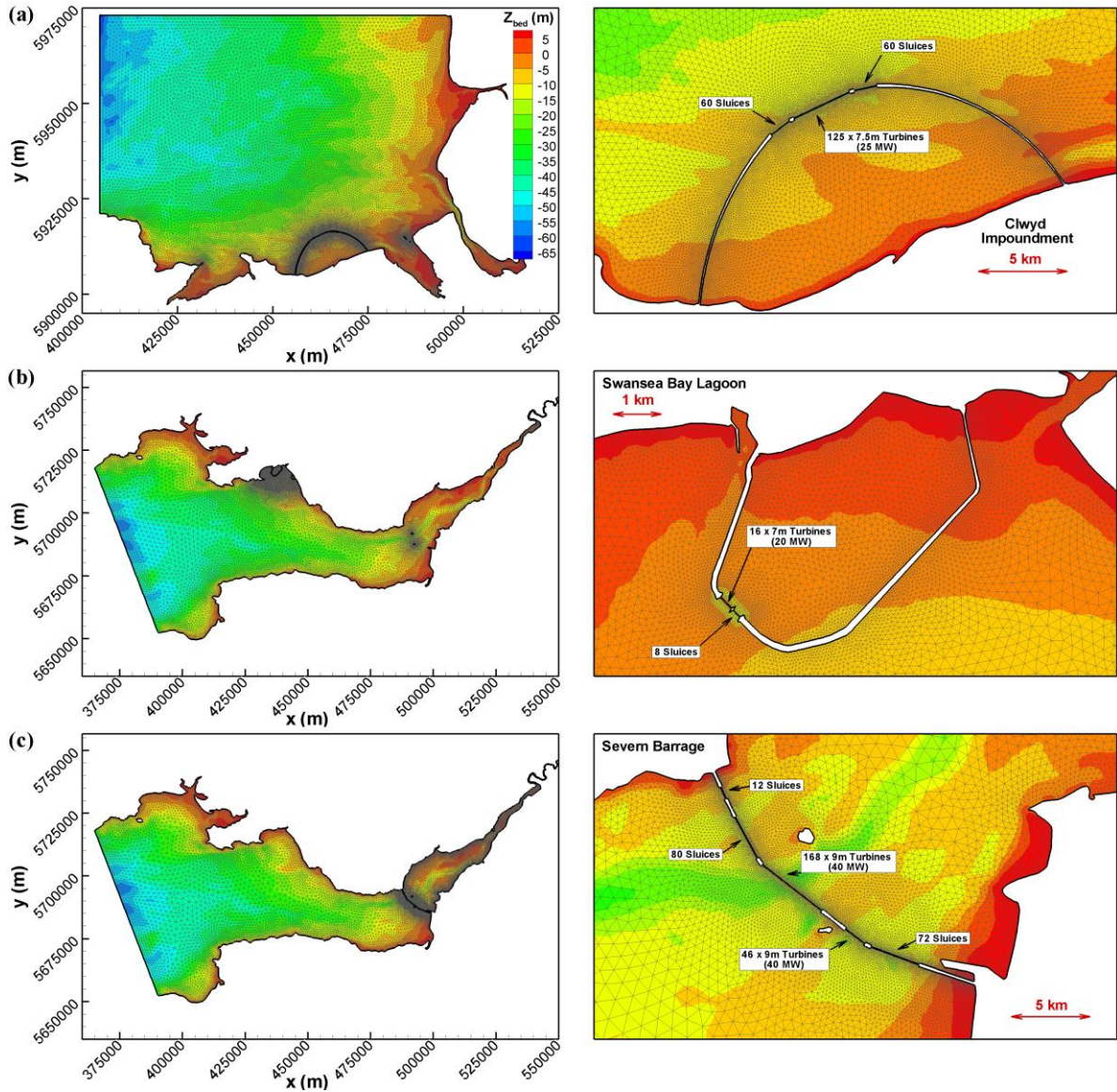


Figure 1 Bathymetry and computational domain for the assessment of: (a) Clwyd Impoundment along the North Wales coast, (b) Swansea Bay Lagoon, and (c) Severn Barrage along the South Wales coast. The figures on the right indicate the mesh refinement in the vicinity of the tidal impoundments.

2 METHODOLOGY

2.1 Hydrodynamic Modelling

2.1.1 Governing Equations and Numerical Scheme

In coastal waters where the flow is primarily contained within a horizontal plane, in the absence of stratification or extensive three-dimensionality, the 2D shallow water equations are sufficiently accurate for predicting the established tidal conditions in the basin. These equations can be written as:

$$\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial G}{\partial y} = \frac{\partial \tilde{E}}{\partial x} + \frac{\partial \tilde{G}}{\partial y} + S \quad (2)$$

where U is the vector of conserved variables, E and G are the advective flux vectors, while \tilde{E} and \tilde{G} are the diffusive vectors in the x and y directions respectively. S is a source term that represents the effects of bed friction, bed slope and the Coriolis acceleration. Equation (2) can be expressed in detail as:

$$U = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, E = \begin{bmatrix} hu \\ hu^2 + \frac{1}{2}gh^2 \\ huv \end{bmatrix}, G = \begin{bmatrix} hv \\ huv \\ hv^2 + \frac{1}{2}gh^2 \end{bmatrix},$$

$$\tilde{E} = \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \end{bmatrix}, \tilde{G} = \begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \end{bmatrix}, S = \begin{bmatrix} q_s \\ +hfv + gh(S_{bx} - S_{fx}) \\ -hfu + gh(S_{by} - S_{fy}) \end{bmatrix} \quad (3)$$

where u , v are the depth-averaged velocities (m/s) in the x and y direction respectively, h is the total water depth (m), q_s is the source discharge per unit area and g is the gravitational acceleration (m/s²). The variables τ_{xx} , τ_{xy} , τ_{yx} and τ_{yy} represent components of the turbulent shear stresses over the plane. For the source term S , $f = 2\omega \sin\varphi$ refers to the Coriolis acceleration, where ω is the earth's angular velocity ($= 7.29 \times 10^{-5}$ rad/s) and φ is the latitude within the domain. The bed and friction slopes are denoted as S_{bx} , S_{by} and S_{fx} , S_{fy} for the x and y directions respectively and defined as in Xia et al. (2010a).

The computational domains (e.g. Figure 1) were divided into sets of triangular cells to form unstructured meshes for a cell-centred Finite Volume Method (FVM). Roe's approximate Riemann solver (Roe, 1981) including a Monotone Upstream Scheme for Conservation Laws (MUSCL), resolved the normal fluxes across each cell interface, following a procedure known as the predictor-corrector time stepping, to satisfy second-order accuracy in time and space (Godunov, 1959). A thin film algorithm for the treatment of wetting and drying fronts was also adapted for intertidal regions (Falconer and Chen, 1991).

Regarding stability, the numerical model was based on a Total Variation Diminishing (TVD) scheme, which is an explicit algorithm and is therefore intrinsically stable, provided the Courant-Friedrichs-Lewy (CFL) number is less than unity. Consequently, predicted hydrodynamic parameters were not prone to the generation of non-physical solutions and were suitable for modelling the high-velocity flows which are triggered through the operation of tidal range structures (particularly the turbines), as for the studies reported herein. Nonetheless, it was ensured that the maximum CFL number was consistently < 1.0 for the current simulations, using a time step of $\Delta t = 0.5$ sec in all cases.

2.1.2 Numerical Model Boundary Conditions

For interfaces between cells and closed boundaries the normal flow flux is set to zero, with the following assumptions applied for a slip condition:

$$u_{bn} = 0, u_{bt} \neq 0 \text{ and } h_b = H_L \quad (4)$$

where u_{bn} and u_{bt} are the velocity components normal and tangential to cell faces as $u_{bn} = u_b \cos a - v_b \sin a$ and $u_{bt} = u_b \sin a + v_b \cos a$ respectively. The value a corresponded to the angle of the interface to the x and y coordinate system used for the computational domain. u_b and v_b are interface state velocities, expressed in the coordinates of x and y . h_b is the average water depth between the connecting nodes, whereas H_L is the water depth of the entire cell. For a slip condition, the transverse velocity was defined according to cell-centred values. The same applies between wet and dry cells in the domain interior, where a value of $H_L = 0.10$ m was used as a threshold for classifying a cell as being active.

If flow across the interface of a cell and a boundary is non-zero, then it is by definition an open boundary where fluxes are calculated in time according to imposed information. The known input for tidal flows can typically be either water elevation or total discharge values. For a given water elevation time series, h_b can be calculated at each step from known values. The new velocity at the interface nodes is estimated through the formulation of Sanders (2002) to eliminate the reflection of waves generated at seaward boundaries:

$$u_{bn} = u_{Ln} + 2(\sqrt{gH_L} - \sqrt{gh_b}) \quad (5)$$

If the total discharge (Q_i) through an i boundary comprising N nodes is provided, then the unit discharge at each boundary node (q_j) is calculated as:

$$q_j = \frac{h_j^{5/3}}{\sum_{j=1}^{N-1} 0.5(h_j^{5/3} + h_{j+1}^{5/3})b_j} Q_i \quad (6)$$

where h_j is the water depth at the particular node and b_j is the distance between nodes j and $j+1$. Subsequently, h_b and u_{bn} are solved iteratively according to the formulae of Sleight et al. (1998) as:

$$q_{bn} = h_b u_{bn}, \quad h_b = (u_{Ln} + 2\sqrt{gH_L} + u_{bn})^2 / 4g \quad (7)$$

For both water level and outflowing discharge boundaries, it was assumed that the velocities transverse to the interface were subject to the cell-centred values (i.e. $u_{bt} = u_{Lt}$). However, for inflowing discharge boundaries the flow direction was specified as described by Anastasiou and Chan (1997), thus dictating the components of u_{bt} and u_{bn} . In turn, these local coordinate velocities were transformed on the x - y coordinate system, before being imported to the main solver for the next iteration.

The above formulations provide standard expressions for the boundary conditions, as used in the 2-D hydrodynamic simulations for coastal processes. Before considering the simulation of tidal impoundments, the unobstructed tidal regimes were simulated for validation purposes, to ensure the satisfactory agreement of the predictions against observed data. More details on the validation studies for North Wales and the Severn Estuary are not repeated herein as they can be found in Angeloudis et al. (2016) and Xia et al. (2010a) respectively.

2.1.3 Treatment of flow and power production through hydraulic structures

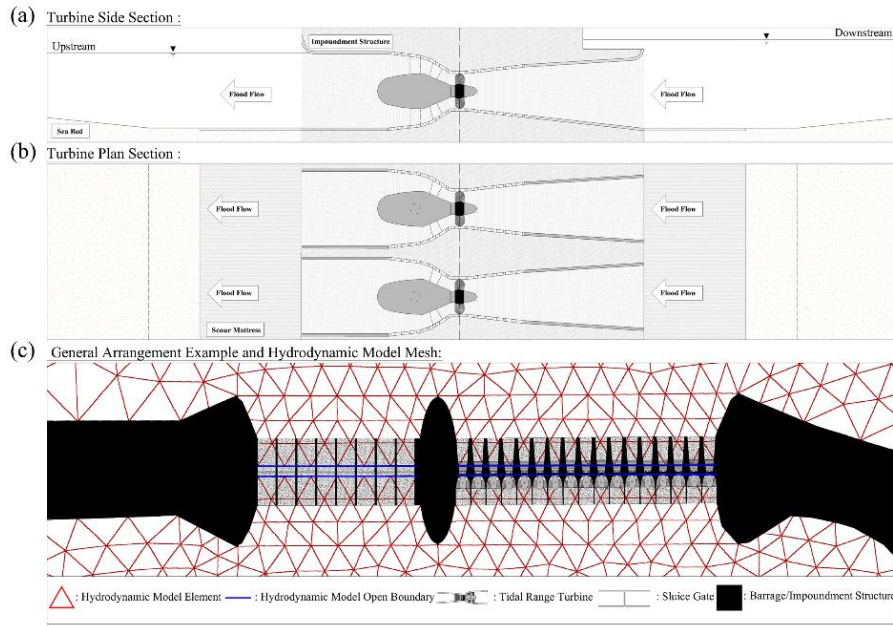


Figure 2 Schematic illustration of the general design of turbine caissons for: (a) cross-sectional, (b) plan view, and (c) a comparison of how the turbine section may actually look like and how it is represented in a coastal hydrodynamic model as a series of open boundaries that dynamically link the downstream with the upstream side of the impoundment.

The operation of a tidal impoundment primarily involves two types of hydraulic structures, i.e. turbines (Figure 2(a-b)) and sluice gates. At certain points during a tidal cycle, once a sufficient water head difference has been facilitated across the two sides of the structure, then water is allowed to flow through the turbine sections and hence generate power by forcing the rotation of the turbine blades. This mode is sustained while power production is efficient, an aspect dependent on the specifications of the turbines in place. Meanwhile, sluice gates supplement the transfer of water volume during the emptying and filling stages of operation. This, in turn, serves two purposes: (a) to maximise or minimise the water level in the impounded area, to facilitate a greater water head difference on the subsequent tidal phase, and (b) to mitigate environmental impacts by contributing to the maintenance of the upstream tidal range wherever possible. The manner in which these structures perform is dictated by the operation regime adopted for the tidal power plant, e.g. ebb-only, flood-only or two-way generation. For this analysis, ebb-only and two-way generation were considered, with a particular focus on the latter. Their mode sequence is schematically demonstrated in Figure 3. For more information on tidal range plant

operation, the interested reader is directed to previous work (e.g. Baker, 1984; Xia et al., 2010b; Aggidis and Benzon, 2013; Angeloudis et al., 2015).

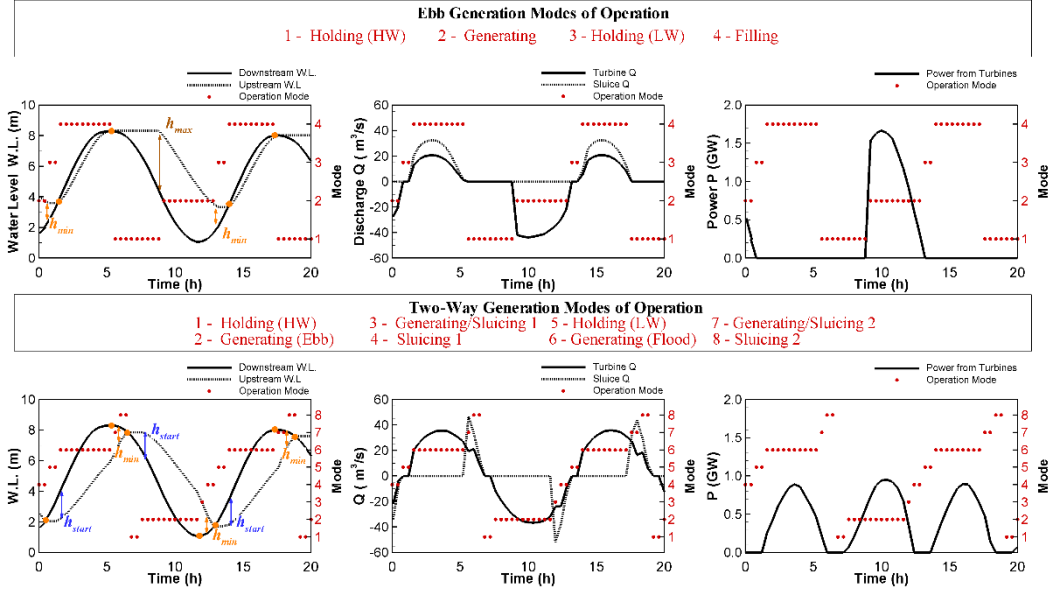


Figure 3 Two-way generation operation applicable for the Clwyd and Swansea Bay lagoons and Ebb generation regime imposed for the STPG scheme of the Severn Barrage. The numbers are indicative and are based on the specifications and tidal conditions of the hypothetical Clwyd Lagoon along the North Wales coast (Figure 1(a)) (Angeloudis et al., 2016).

A technique of domain decomposition can be implemented to represent plant operation processes within a regional hydrodynamic model efficiently. This approach is followed when representing a tidal impoundment by using two subdomains, one upstream and another downstream; a method widely reported (Burrows et al., 2009; Ahmadian et al., 2010; Xia et al., 2010a,b,c; Cornett et al., 2013; Angeloudis et al., 2016). Open boundary conditions connecting the subdomains are specified in the region of flow control structures, e.g. turbines and sluices (Figure 2), with the flow rate through them dictated by the operational stage of the power plant.

Figure 2(c) provides an example of how domain decomposition was applied. The sketch indicates a turbine and sluice configuration for the particular proposal, on top of the mesh generated for the regional-scale model. What should be appreciated for these simulations, as well as the aforementioned studies encountered in the literature adopting the domain decomposition method, is that the actual geometry of the turbines (e.g. Figure 2a-b) and sluice gates is not directly modelled. This is a limitation primarily on the grounds of simplicity and computational efficiency. The turbine and sluice flow is typically the subject of high-resolution near-field hydrodynamic models that normally extend to three dimensions (Keck and Sick, 2008). Nonetheless, three-dimensional flow conditions will also develop in the immediate locations downstream and upstream of the turbines and sluice gates, as shown by experimental investigations (Jeffcoate et al., 2011, 2013). Such detail is: (a) beyond the scope of the two-dimensional model capabilities reported herein, and (b) it has been questionable whether such high resolution would impair the predictions beyond the area close to the impoundment turbines/sluice gates. The previous experimental results indicate a three-dimensional flow behaviour extending to a distance of $20D$, where D is the diameter of the turbine throat area. (Jeffcoate et al., 2013). For the regional scale modelling reported in the paper, these are confined to the cells immediately adjacent to the hydraulic structures,

A straightforward approach used to calculate the flow driven by a water head difference H is the orifice equation (Baker, 2006):

$$Q = C_d A \sqrt{2gH} \quad (8)$$

where C_d is the discharge coefficient, a parameter specific to the design of the hydraulic structure, and A the throat flow area (m^2). The value of H is the difference at the cells at the upstream and downstream sides of the open boundaries. Typically, the sign of H dictates the direction of the flow (i.e. either emptying or filling the upstream area). In the absence of more detailed information due to the commercial sensitivity of turbines and sluices, equation (8) has been used extensively to represent the discharge through impoundments (e.g. Ahmadian et al., 2010; Zhou et al., 2014a). For sluice gates, equation (8) can be considered as an acceptable empirical approach to calculating the flow through a gate, even though there is the remaining uncertainty over the variation of C_d (Bray et al., 2016; Xia et al., 2010a), which was given the value of unity for simplicity. For bulb turbines, it has been argued that equation (8) may be an oversimplification of

their behaviour (Xia et al., 2010b). Therefore, an alternative approach was followed, where the discharge and power generated were computed using a hill chart (Figure 4), as in Falconer et al. (2009) and Cornett et al. (2013). These relate the maximum power, hydrostatic head and discharge for different size turbines (Goldwag and Potts, 1989; Falconer et al., 2009).

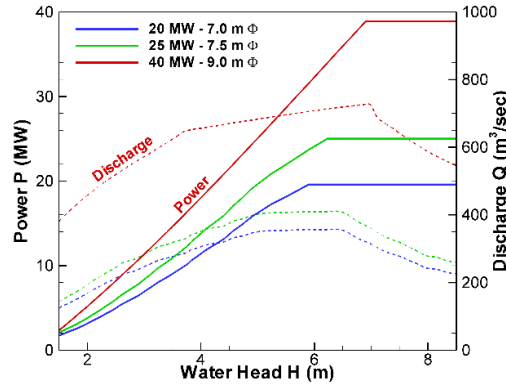


Figure 4 Hill charts for a 25 MW 7.5 m diameter turbine for the Clwyd Impoundment, a 20 MW 7 m diameter turbine for the Swansea Bay Lagoon and a 40 MW 9 m diameter turbine for a Severn Barrage.

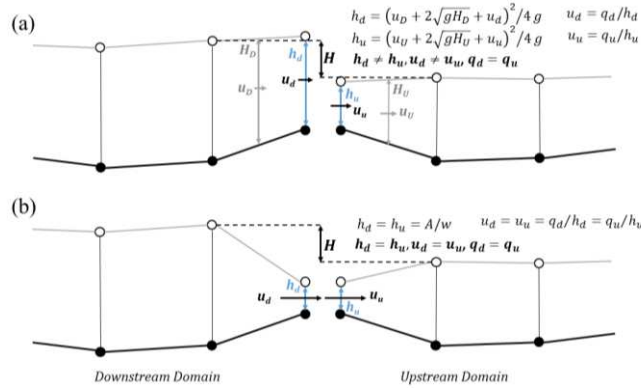


Figure 5 Schematic representation of flow driven from a head difference H through a flow area A across a cell width w using two different approaches: (a) conventional discharge boundaries, (b) refined representation in this study.

It was assumed that the minimum flow area at a turbine section is given by $A_{turbine} = \pi r^2$, where r is the radius of the turbine section in m. By observation of the potential turbine flowrates of Figure 4, it can be discerned from first principles ($V=Q/A$) that the velocities developed can easily exceed 10 m/s. Such a magnitude would influence the velocity field, water quality, sediment transport, morphological and ecological processes locally and to a regional extent, due to the corresponding momentum of the water jet induced through the constricted area. It is of interest to test certain formulations for their effect on the momentum flow through the depth-averaged model. The first approach treats the boundaries as of the conventional discharge type, i.e. the flow is distributed to the boundary nodes through equations (6) and (7). The second approach is a refined treatment to conserve the momentum of the inflow. This was accomplished by setting the water depth across the boundary to a value that forces the cell interface area to match the combined cross-sectional area of the hydraulic structures. This means that an equivalent depth h_b from equation (7) is provided, so that $h_b \cdot w_b = A_{turbine}$, where w_b is the interface width of the particular cell element.

The main differences between the two hydraulic structure representation approaches can be appreciated in the schematic diagram of Figure 5. In the refined representation, by equating the flow area and predicting the same velocity values at the linked subdomain boundaries, the advective fluxes are conserved during the operation. As a result, aside from the model acknowledging a more realistic velocity magnitude (e.g. $u_{bn} = Q_{turbine}/A_{turbine}$) at these interfaces, the momentum transferred between domains is conserved. The boundary condition in each of the subdomains of Figure 5b resembles the supercritical flow boundary described by Anastasiou and Chan (1994) since both water levels and discharge are explicitly specified at the boundary nodes.

2.2 Tidal Impoundment Case Studies

The selection of the impoundment case studies was based on their varying scale, which provides an opportunity to assess how significant the hydraulic structure representation is in providing the numerical results for different settings. Moreover, the design of the Severn Barrage and Swansea Bay Lagoon, introduced previously, have been under consideration for development. Thus, the analysis demonstrates the potential of such tools for optimisation purposes, while also acknowledging their associated limitations. Numerical models were setup to simulate the operation of the three tidal range schemes. In Figure 1, an overview of the area bathymetry, the shape, location and the overall configuration of the tidal impoundments can be observed. A summary of their main specifications is outlined in Table 1 for completeness.

Table 1 Specifications of the Tidal Impoundments Considered

Specifications	Tidal Impoundment Case Studies		
	Clwyd Impoundment	Swansea Bay Lagoon	Severn Barrage
Operational Scheme Considered	<i>Two-Way</i>	<i>Two-Way</i>	<i>Two-Way / Ebb Only</i>
Driving head h_{max} (m)	2.5	2.5	2.5/4.0
Minimum generation head h_{min} (m)	1.5	1.5	1.5
Impounded Surface Area (km ²)	126.0	11.6	573.0
Turbine Number	125	16	216
Turbine Capacity (MW)	25	20	40
Turbine Diameter (m)	7.5	7.0	9.0
Turbine Flow Area (m ²)	5522	616	13741
Sluice Flow Area (m ²)	5000	800	35000
Total Capacity	3125	320	8640
Length of Impoundment (km)	27.8	9.6	16.1

2.2.1 Clwyd Impoundment

The Clwyd Impoundment (Figure 1a) is a concept of a tidal range structure (Anderson, 2012) strategically positioned to: (a) protect vulnerable communities (such as Towyn and Rhyl on the North Wales coast) from coastal flooding, (b) counter impending detrimental effects of sea-level rise, and (c) act as a source of tidal energy. The 3125 MW capacity specification of turbines and sluices have been determined for this impoundment through a combined 0-D and 2-D optimisation process described in Angeloudis et al., (2016). The lagoon shape and distribution of the 125×25 MW, 7.5 m diameter, turbines and sluice gates has been primarily based upon the regional bathymetry, but also to highlight some operational aspects that could be useful when deciding on the distribution of the sluice gates. However, for the design tested herein, other factors have not been considered, such as the sea bed geomorphology and the presence of competing renewable energy schemes currently in the region (e.g. wind farms), that would invariably affect the shape and setup of the impoundment.

2.2.2 Swansea Bay Lagoon

The Swansea Bay Lagoon (Figure 1b) is a tidal range scheme initiated by Tidal Lagoon Power Plc (2014) that proposes the construction of an artificial lagoon along the Swansea Bay coast to impound 11.6 km² for the purpose of tidal power generation (Baker et al., 2006; Thomas et al., 2014; Waters and Aggidis, 2016a,b). At the time of writing, this project has been granted planning consent, and if constructed with a potential installed capacity of 320 MW through 16 × 20 MW, 7.0m diameter, bulb turbines, it would become the largest tidal range project to-date. In spite of this, it is perceived as a pilot scheme for larger projects that would be either within the Severn Estuary or beyond, such as along the North Wales coast, similarly to the Clwyd Impoundment. The shape and lagoon specifications were specified to match the available information provided by the Development Consent Order application of the project and subsequent discussions with the company (TLP, 2015). The simulations assume a total sluice gate area of 800 m² in the absence of more detailed information. Also, the lagoon was intentionally modelled to operate under a two-way generation mode (Figure 3) for a driving head of 2.5m and a minimum head of 1.5m for consistency with the operation sequence optimised for the Clwyd Impoundment (Angeloudis et al., 2016).

2.2.3 Severn Barrage

A tidal barrage in the Severn Estuary has historically been the most discussed tidal range project in the UK, with the initial idea going back over a century (Brown, 1976; Waters and Aggidis, 2015). Over time, there have been numerous variants considered, which however have repeatedly fallen short towards adequately addressing issues such as the high construction cost and the satisfactory identification and mitigation of potential environmental impacts. One of the most detailed proposals was the STPG (1989) scheme of a Cardiff-Weston barrage (Figure 1c), consisting of 216 × 40 MW, 9.0m diameter bulb turbines, 166 sluice gates, ship locks and other hydraulic structures (DECC, 2008). If constructed, it would amount to a capacity of 8640 MW, which if operated optimally could harness over 5% of the current electricity needs for the UK. The present model for the STPG scheme builds upon the previous work of Xia et al., (2010a,b,c) where a range of modifications was proposed to optimise the operational efficiency of the structure. This project has also been extensively

studied through numerical modelling to assess its influence on water quality processes (Kadiri et al., 2012; Ahmadian et al., 2010), as well as far-field effects (Zhou et al., 2014a,b), before and following optimisation. The design was tested here under the same two-way generation regime, as for the other case studies, assuming that the turbine technology and caissons were constructed in a manner that enables such an operation (Table 1). However, the STPG proposal was originally designed based on the principles of ebb-only generation (Figure 3) and was also modelled here accordingly for completeness, with more details available in Xia et al., (2010c).

3 RESULTS AND DISCUSSION

3.1 Impact of turbine boundary treatment on hydrodynamic conditions

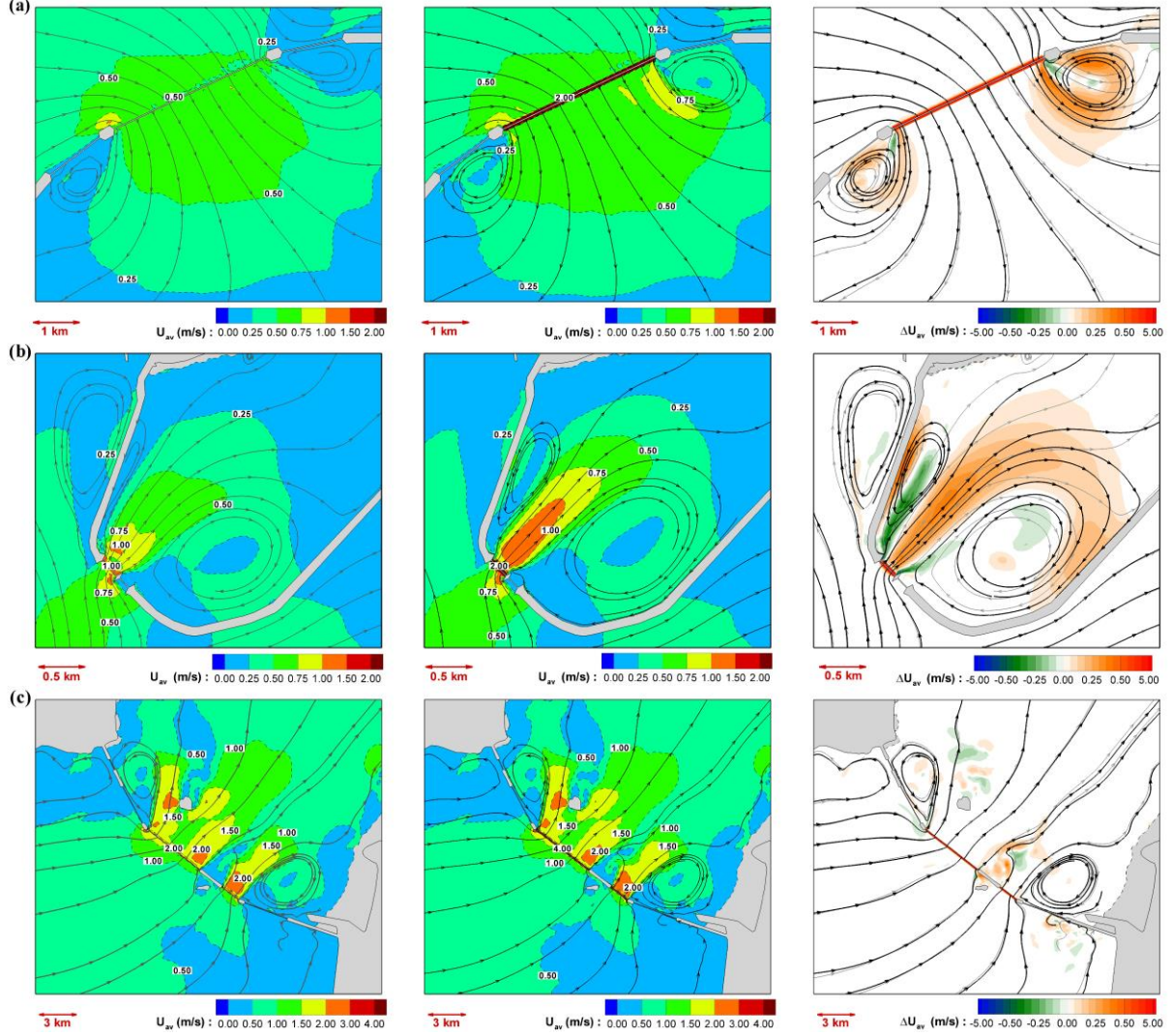


Figure 6 A comparison of the turbine wakes and the subsequent recirculation between a conventional velocity boundary and a refined boundary that matches the actual flow area through the turbine. Prediction at the peak flow rate predicted during flood generation respectively for the three case studies. The figures on the left correspond to the predictions assuming a conventional velocity boundary, the middle ones adopt the refined treatment and the far right provide the relative difference in magnitude of the two. The flow direction is indicated with grey streamlines for the normal representation and black for the refined approach.

An appreciation of the flow regime under a bi-directional turbine operation can be acquired from the instantaneous streamline/contour plots, as illustrated in Figures 6 and 7. The velocity scale for all studies has been related to the peak velocities on the related Admiralty charts for the Clwyd Impoundment (Liverpool Bay), Swansea Bay Lagoon (Swansea) and the Severn Barrage (Severn Estuary), where the peak velocities cited on the respective charts are 0.87 m/s, 0.8 m/s and 1.8 m/s respectively. Hence, the maximum velocity contour has been set at 2 m/s for the Clwyd and Swansea Bay impoundments and 4 m/s for the Severn Barrage. These figures correspond to the maximum turbine flow rate instances during the flood (Figure 6) and ebb (Figure 7) generation and are meant to highlight the counter-rotating recirculation zones formed adjacent to the turbine wake. Due to the positioning of the turbines, which force the otherwise undisrupted flow to enter or exit the area through a small section of the impoundment, large recirculation zones are inevitable, particularly where the turbines are not widely distributed across the impoundment walls.

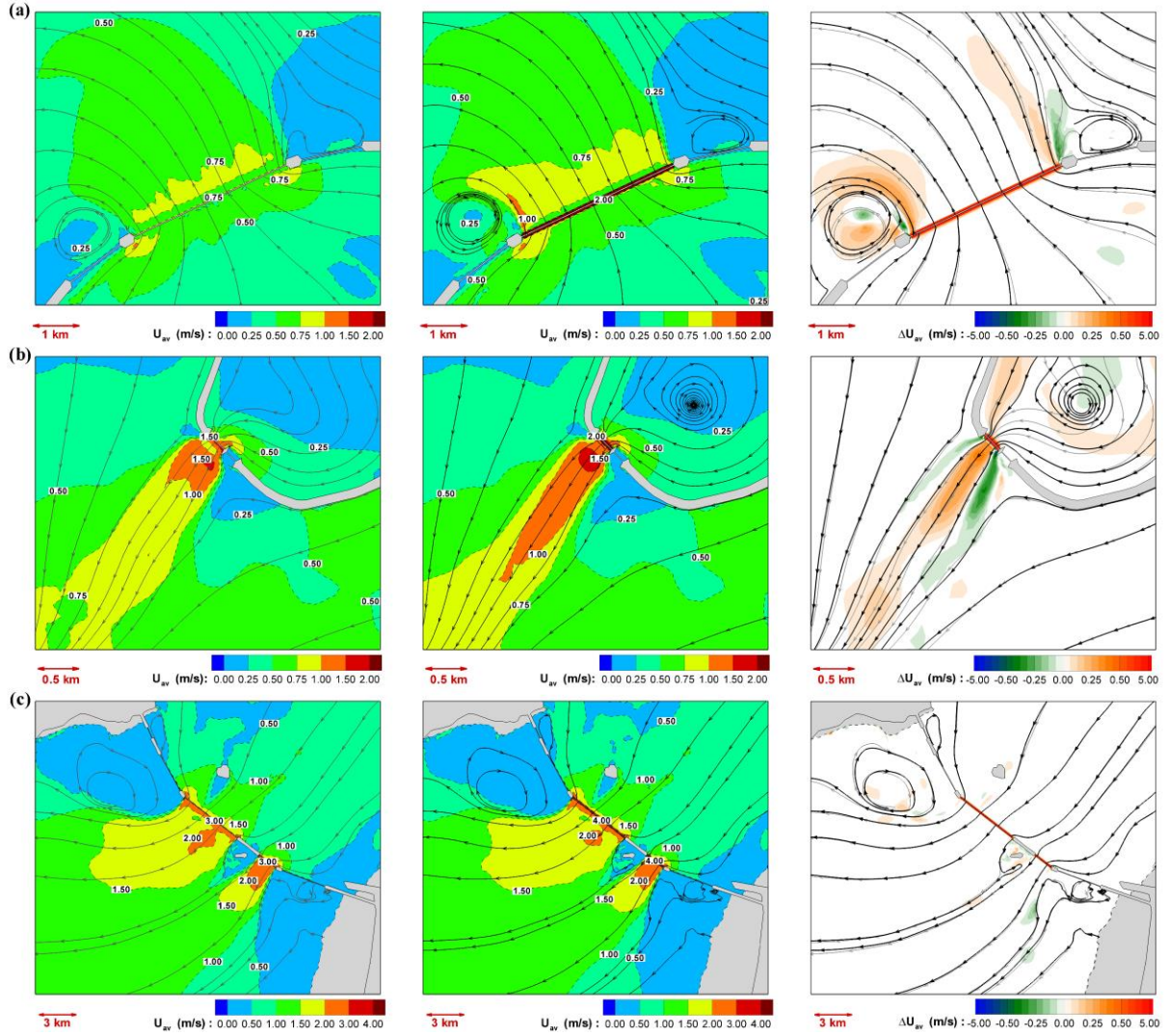


Figure 7 A comparison of the turbine wakes and the subsequent recirculation between a conventional velocity boundary and a refined boundary that matches the actual flow area through the turbine at the peak flow rate predicted during ebb generation respectively for the three case studies. The figures on the left correspond to the predictions assuming a conventional velocity boundary, the middle ones adopt the refined treatment and the far right provide the relative difference in magnitude of the two.

Results show that the numerical model hydraulic structure treatment can play a significant role in the predictions of the velocity field. There are several distinct differences between the two approaches, which are particularly pronounced for the smaller schemes. Initially, if the momentum is conserved according to the confined flow area, then the turbine wake length becomes more significant. For the instantaneous conditions of Figure 6, the wakes of the Clwyd Impoundment and the Swansea Bay lagoon were under-predicted through the conventional approach. This can be observed by the increased velocity contours once the flow momentum is conserved through the refined treatment. For the Severn Barrage, depending on the location and the local bathymetry the wake length varies, but these results seem to be largely independent of the boundary treatment as shown in Figure 6(c).

Another aspect affected is the flow pattern. Grey streamlines in Figures 6 and 7 were produced from the models where the turbine and sluice boundaries have been treated as conventional discharge types. Similarly, the equivalent black streamlines correspond to the refined boundary simulations. It is clear that larger vortices develop for the smaller schemes through the refined representation. Due to the momentum and mass transferred, at the particular instance of Figure 6, recirculation zones occupy approximately 4.98, 3.14 and 27.80 km² of the Clwyd Impoundment, Swansea Bay Lagoon and Severn Barrage areas respectively (i.e. 3.98, 27.0 and 4.85% of their respective upstream plan surface areas respectively). Without the effects of the water jet momentum these values were reduced to 2.82, 2.22 and 27.80 km². The low-velocity area in the recirculation centroid can be prone to the accumulation of scalar quantities e.g. suspended sediment concentrations which can, in turn, lead to sediment deposition if the zone persists for an extended duration (i.e. due to the “tea cup effect”). As the size of the recirculation zone increases, so does the likelihood of scalars to be transported and entrapped within the

particular stagnant regions. Therefore, it is essential for the momentum to be conserved within the model to enable a reliable assessment of interconnected physical processes.

Differences in velocity magnitude, as illustrated through the contour colours, can similarly be significant as shown by the relative difference plots of Figure 6. For the Severn Barrage, these boundary treatment effects were not as apparent (Figure 6c), suggesting a negligible deviation relatively to the entire wake size. This can partly be attributed to the greater water depth facilitated by the local bathymetry close to the turbine and sluice gate sites upstream and downstream of the Severn Barrage. While the momentum is conserved, as in other schemes, the effects are not fully appreciated in the depth-averaged predictions reported herein. Even so, these would still be contained to the location opposite the hydraulic structure openings and considering the wake size (notice the different scale in Figures 6c and 7c), the impact of the boundary treatment is not as relatively prevalent as for other cases. On the other hand, for the Clwyd Impoundment and Swansea Bay Lagoon, the turbine flow appears to be more focused featuring greater velocities at its centre which are also predicted due to the gradual reduction of the water depth away from the hydraulic structures.

It can be observed that similar outcomes for the wake size, recirculation zones and velocity magnitude are also characteristic during ebb generation (Figure 7a, b, and c). Nonetheless, the Clwyd Impoundment results suggest relatively low-velocity magnitudes (<1.0 m/s) locally, even though it involves a substantial turbine flow area (see Figures 6 and 7). This is because the 125 turbines were more widely distributed across the deeper section of the impoundment, to mitigate high-velocity wake effects. It can be seen that this practice may seem advantageous as it can lead to smaller relative recirculation zones and more confined hydrodynamic impacts. However, for practical applications and considering the cost associated with low head bulb turbine caissons, distributing turbines may be cost prohibitive, which would explain the proposed configurations for Swansea Bay Lagoon and the original Severn Barrage.

An exact percentage for the disparity between actual and predicted velocities is difficult to pinpoint, due to the variable flow during plant operation. However, the underlying assumptions of the two boundary representation approaches can provide an indication. For the Clwyd Impoundment, a turbine flow area of 5522 m^2 is distributed over 3.15 km (Table 1). Therefore, to establish this area at the boundary interface, a hydraulic depth of $h_b \approx 1.75 \text{ m}$ was imposed, as illustrated in Figure 5(b). In contrast, for the conventional discharge boundaries, h_b varies in time according to adjacent cells as in equation (7). For instance, the tidal range at the turbine section of the Clwyd Impoundment implies that h_b can roughly be in the range of $7.5\text{--}15.5 \text{ m}$. These values are given as an example but could be additionally influenced by localised conditions. Despite h_b from the two approaches being different, an equivalent flowrate was imposed to satisfy mass conservation. Consequently, a conventional discharge boundary in the Clwyd scheme underestimated velocity levels at the interface nodes by at least 430%.

3.2 Tidal Impoundment Scheme Impact

Velocity maxima post-construction against the tidal flow in the absence of the impoundments are compared in Figure 8. There is an increase in the velocity magnitude according to the orientation of the hydraulic structures. For the Clwyd Impoundment, in particular, the turbine wake affects the hydrodynamics closer to the coast, where the higher velocities are attributed to the persisting wake momentum and the reduced depth due to the bathymetry. Such currents could resemble the behaviour of rip currents, and may interfere with other socio-economic activities within the lagoon such as sailing and swimming. Careful consideration is necessary if these hydrodynamic effects are not to be mitigated at the expense of power production. A similar pattern can be observed for the Swansea Bay Lagoon, where almost a third of the impounded area would at times be subject to currents exceeding 0.9 m/s , which is regarded as a typical “average human swimming speed”. For the Severn Barrage, while the turbines and sluices are positioned according to the previous direction of the flow, and therefore the hydrodynamic conditions are similar as before, velocities greater than 0.9 m/s are already encountered for much of the estuary in the absence of any tidal range schemes.

The right-hand side plots of Figure 8 were intentionally produced on the same scale to facilitate a comparison. An initial overview indicates that as the project size increases, so does the deviation from the original conditions. This is particularly applicable here as demonstrated by the relative difference for the Severn Barrage (Figure 8c), followed by the Clwyd Impoundment (Figure 8a) and lastly by the Swansea Bay Lagoon (Figure 7b). The STPG design of the Severn Barrage greatly reduces the incoming water volume in the estuary, leading to an obvious deceleration (Figure 7c) of the Bristol Channel currents as also discussed by Xia et al., (2010c). For the two lagoons, due to their relatively smaller scale and configuration, the effects are largely confined to the region near the turbines and sluice gates; an aspect attributed to their limited interference towards major coastal and estuarine processes.

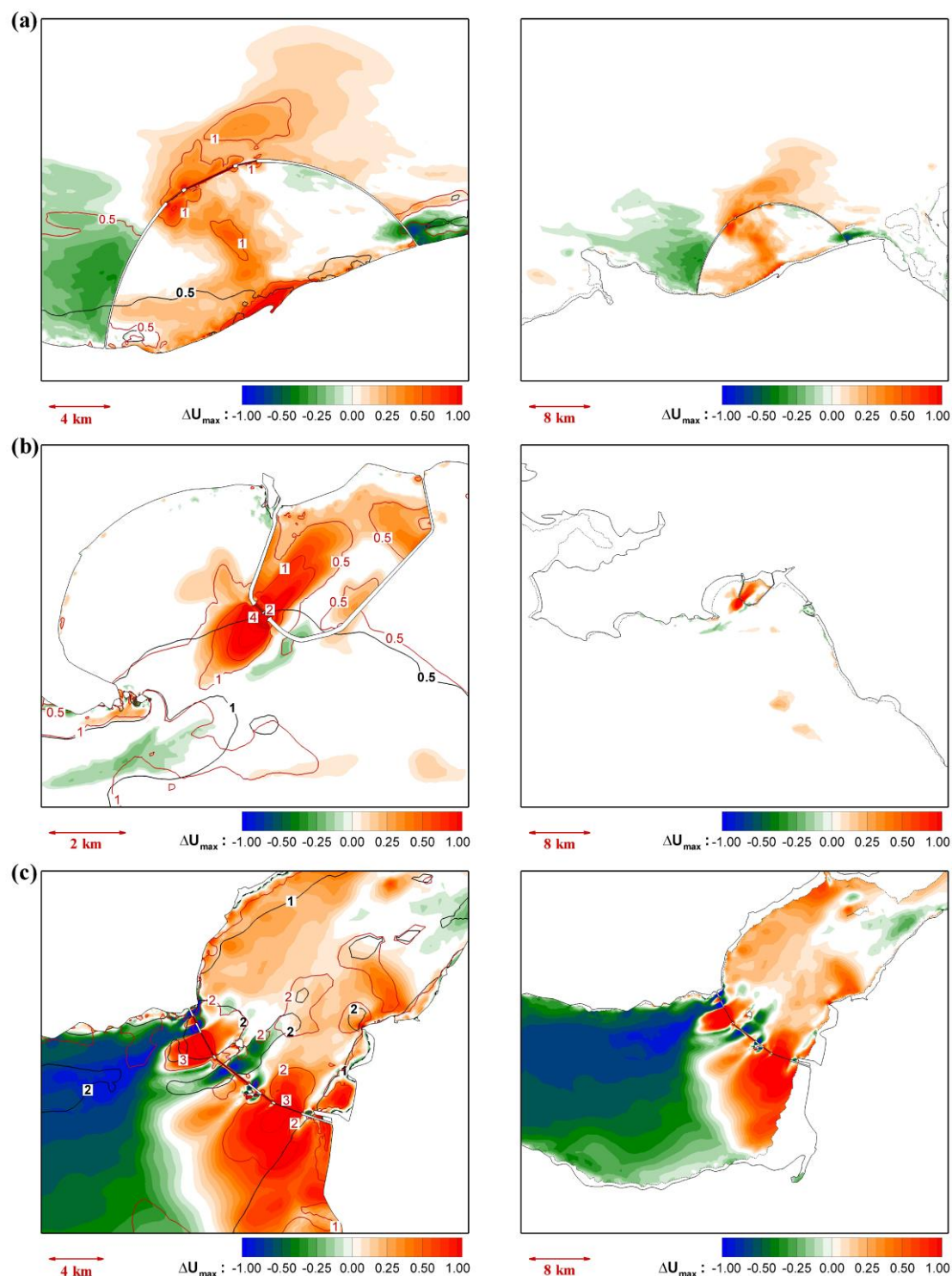


Figure 8 Velocity maxima deviation before and after construction of the impoundments for: (a) Clwyd Impoundment, (b) Swansea Bay Lagoon and (c) Severn Barrage (STPG design) for two-way generation. Line contours are also included to indicate the velocity maxima before (black) and after (red) the structures is in place.

3.3 Power Generation

Transient water level differences upstream and downstream of the three tidal range schemes predicted by the simulations enable an evaluation to be made of the energy extraction potential in time through an approach that accounts for the regional hydrodynamic impact of the impoundment. Simulations were conducted over a sufficient period that covers both spring and neap tidal regimes, so as to obtain a holistic view of the tidal power plant operation. This is illustrated in Figure 9 where the deviation in power production is noticeable in the transition from spring to neap tides. Of interest is the potential of tidal range schemes between North and South Wales to complement one another due to the tidal phase difference. Results

suggest that an almost continuous contribution of tidal energy to the national electricity grid can be facilitated during spring tides. During neap tides, the concurrent operation of tidal impoundments certainly reduces the duration of power generation gaps, but could benefit from additional projects across the UK to further close this gap. This outcome is in line with previous investigations of Burrows et al., (2009b) and Wolf et al. (2009), and could guide the strategic site selection process of future proposals.

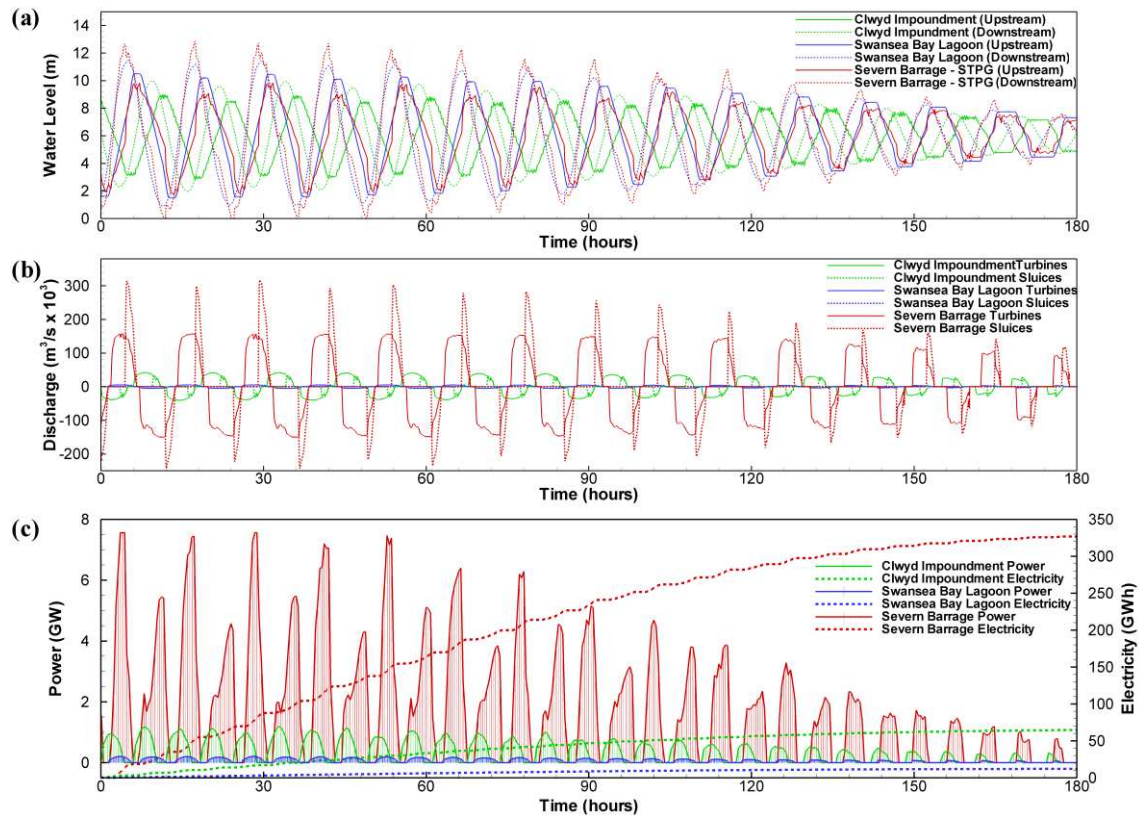


Figure 9 (a) Water Level Downstream and Upstream of the impoundments (b) Combined hydraulic structure flow rates and (c) Power Generated over a 180 h period during an even mixture of spring and neap tidal conditions for the Clwyd Impoundment, Swansea Bay Lagoon, and a Severn Barrage running under a two-way generation operation.

Attention should be drawn to the significance of the wetted surface area on the power output. A barrage across the Severn Estuary of 16.1 km (Table 1) is capable of impounding an area of 573 km² and tap into a superior energy source, in comparison with the other 9.6 km and 27.8 km long walls for the Swansea Bay and Clwyd impoundments respectively. The latter only impound a fraction of the planned surface area (Table 2) but correspond to lesser environmental impacts (Figure 8). Moreover, if the impoundment design and operation is particularly disruptive to the existing tidal current conditions, then this is likely to affect the regional tidal dynamics and as a result deviate from the preliminary electricity estimates to be gained. Table 2 summarises results from a 0-D modelling methodology (Angeloudis et al., 2015; Aggidis and Benzon, 2013) that includes information for the tidal conditions at the turbine sections, based on the established tidal regime. Next to these results are the equivalent predictions from the 2-D hydrodynamic models that account for the presence of the structures. For the Clwyd and Swansea Bay impoundments, 0-D model results are in good agreement with the hydrodynamic model predictions, since the deviation is below 10%. On the other hand, for the Severn Barrage, these become substantial due to the footprint of the STPG proposal on the regional flow field and the significant phasing of the tide along the estuary; this same deviation would apply to larger lagoons and where a 0-D analysis is less appropriate.

Table 2. Typical Annual Energy Prediction summary according to simulations spanning spring-neap tidal cycles adopting the operational sequences of Figure 3.

Tidal Impoundment Studies	Case	Power Generation Predictions (TWh/yr)		Hydrodynamic Impact on Power Production
		0-D Modelling	2-D Modelling	
Clwyd Impoundment		2.74	2.63	3.8%
Swansea Bay Lagoon		0.53	0.49	6.8%
Severn Barrage STPG (Two-Way)		23.4	13.5	42.4%
Severn Barrage STPG (Ebb)		21.5	14.7	31.9%

3.4 Discussion

3.4.1 Numerical Assessment Limitations and Potential

The reliability of such numerical models can be traced back to the assumptions and formulations adapted for the representation of tidal impoundment operations. For example, the validation of the predictions in previous investigations (Angeloudis et al., 2016; Cornett et al., 2013; Ahmadian et al., 2010; Burrows et al., 2009a; Xia et al., 2010a,b,c) has been solely based on the reproduction of the established tidal flow conditions. In this study, the standard formulations used to represent turbine and sluice flow are discussed to highlight how the conventional coastal modelling methodology may differ from what would be encountered in practice. The refinement of the hydraulic structure boundary conditions (Figure 2) and the ensuing results demonstrate how certain aspects can be better tailored to the model applications, e.g. by matching the turbine and sluice areas to the boundary interface area, to conserve momentum during inflow and outflow through the turbines and sluices.

Another factor to be considered is the objective of each investigation. If the desired result of the analysis is purely the determination of the annual electricity production (e.g. Xia et al., 2010b), then the boundary condition refinements for the particular case studies have a negligible impact on power output. Far-field models such as Zhou et al., (2014a,b,c) feature extended boundaries (e.g. to the Continental Shelf) to capture the effects of any changes in tidal resonance, generated at the Continental Shelf. However, their mesh closer to the schemes may be coarser than for regional models with higher resolution and thus more adequate to simulate flow in the immediately surrounding areas. The same applies to water quality studies (Kadiri et al., 2012), where approximate methods of analysing parameters, such as sedimentation and salinity, may not be captured through the flow patterns to the same extent as with accurate hydrodynamic models. Other assumptions are made on the grounds of the numerical modelling limitations. For the far-field study of Burrows et al., (2009b) it was reported that the bathymetry at nodes close to impoundment sluices and turbines were set to 30 m, to ensure the numerical stability without having to reduce the time step impractically for the simulations. This modification can distort the local flow structure, but it is doubtful whether it affects the far-field findings.

Preceding numerical model studies have paved the way to provide an insight into a range of environmental aspects, affected by the operation of tidal range structures. With exponential advances in computational processing capabilities, it could be of interest to develop a unified framework that incorporates methods from all relevant analyses. The desired outcome would be to produce the essential tools suited to the design of these schemes and gradually depart from their inherent assumptions for numerical simplicity. For instance, the more pronounced recirculation zones predicted would invariably affect erosion and sedimentation processes. As a result, it would be useful to examine whether the design can be optimised before construction, by taking the formation of these flow structures into account.

3.4.2 Operation Optimisation

For power generation, it has been argued (Adcock et al., 2015) that 0-D approaches can predict to a remarkable level the potential of a tidal impoundment. The hydrodynamic effects omitted by 0-D modelling predictions has been previously estimated to be in the range of 3-12% (Burrows et al., 2009a). For the Swansea Bay Lagoon and the Clwyd Impoundment 0-D and 2-D power predictions fall within this range. For the STPG scheme, 0-D model predictions substantially deviate from that range; an aspect attributed not only to the structure itself (Figure 7c) but also to its operation regime as shown by the different percentages produced for the ebb and two-way generation (Table 2). For the Severn Barrage study, and that of large lagoons, the assumption that the water surface elevation across the impounded water body remains horizontal, as assumed for 0-D modelling, also becomes invalid. Similar findings have been observed by 0-D and 2-D predictions for large lagoon proposals (Angeloudis et al., 2016; Yates et al., 2013b). These results show that the deviation on power predictions between the 0-D and more sophisticated methodologies will depend on the manner the impoundment interferes with the existing flow, and thus may vary on a case by case basis.

The resource assessment of potential tidal impoundments is initially based on the established flow conditions at proposed sites. Therefore, the success of these projects should be assessed in terms of minimising their impact on the tidal dynamics, not just for the environmental concerns, but also to assure that the power output is consistent with preliminary estimates. It is speculated that a more mindful design of the impoundment General Arrangement could greatly benefit the power production while mitigating many of the environmental implications that may not have been identified in previous proposals. An example of taking advantage of the impoundment arrangement to mitigate stagnant zones can be seen in Figure 6(a) and 6(c) for the Clwyd Impoundment and the Severn Barrage. Sluice gates are placed adjacent to locations prone to recirculation as a consequence of the turbine wake. Therefore, as the sluice flow is directed through the epicentre of such vortices, they are successfully dissipated at certain stages of the operation and are not allowed to persist for any significant periods of the tidal cycle.

As an example of optimisation efforts, studies have more recently focused on the improvement of the Severn Barrage and tidal lagoon design and operation (Angeloudis and Falconer, 2016; Zhou et al., 2014b; Xia et al., 2012). Their results suggest that a two-way operation, including more turbines rather than sluice gates, effectively reduces the environmental

impacts facilitating an improved energy output. Nonetheless, these optimisation methods still allow for improvements, e.g. by informing them to calculate the cost/benefit associated with more sustainable solutions.

4 CONCLUSIONS

A methodology has been presented for the assessment of tidal power impoundments using an unstructured grid coastal model. Key formulations and the representation of an impoundment, turbines and sluices have been discussed to highlight the inherent assumptions in the context of assessing their regional impacts. The aspects highlighted allow for an interpretation of the predictions that acknowledges the uncertainty of what is modelled numerically and the conditions in practice. Subsequently, the treatment of the impoundment boundary conditions, particularly relating to the hydraulic structures (including turbines and sluices), was refined to conserve momentum fully on both the incoming and outgoing flow through the structures. The modifications were assessed for their impact on three tidal impoundment proposals, including a previous proposal of the Severn Barrage (namely the STPG original scheme), the Clwyd Impoundment and the Swansea Bay Lagoon proposals. It has been shown that momentum conservation at the open boundaries is important for accurate 2-D modelling of the hydrodynamic conditions for all three projects, but particularly for smaller schemes, which in this case correspond to the Clwyd Impoundment and the Swansea Bay Lagoon.

The model resolution was locally refined in the vicinity of the impoundments and the flow patterns produced demonstrate that extensive recirculation zones develop depending on the distribution of the impoundment turbines. The proposed boundary treatment refinements show that the vortex size and location may be affected by the manner turbine, and sluice gate operations are represented in the hydrodynamic model. Clearly for the design of a barrage or lagoon, it is desirable to reduce any recirculation zones to a minimum to reduce: (i) hydropower losses, (ii) rapid siltation (i.e. due to the “tea-cup effect”), (iii) strong currents, (iv) pollutant trapping and (v) adverse hydro-ecological conditions.

The comparison of the energy extracted among the three schemes indicated that it is theoretically desirable to maximise the area impounded. It was shown that even though the Severn Barrage is 1.7 times longer than the Swansea Bay Lagoon, it can generate 27 times the electricity when operated under the same two-way generation regime. On the other hand, depending on the arrangement of this project, this may extensively affect the local tidal conditions, and therefore impair the electricity estimated from simplified approaches. The 2D methodology can account for the hydrodynamic effects to yield more realistic electricity predictions. Recent studies have shown that two-way generation can produce an equivalent power output to that obtained for an ebb-only generation, and also have the benefit of reducing many of the original hydro-environmental concerns (e.g. significant inter-tidal habitat loss).

For the optimisation of tidal impoundments, research needs to focus on determining a suitable configuration and design of turbines that minimises undesirable impacts on the marine environment, water quality and sedimentation conditions, both upstream and downstream of the site. For such studies, it is imperative that numerical modelling tools are continually improved and applied to ensure the success of these renewable energy schemes, including accurate momentum conservation through turbines and sluices.

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